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Urban Adaptation to Climate Change: Climate Refuge Networks as a Strategy to Mitigate Thermal Stress

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Abstract

Urban areas face rising risks from extreme heat due to climate change, intensifying thermal stress and exacerbating social inequalities. Urban climate refuges—cool, accessible indoor and outdoor public spaces that maintain their ordinary functions—are increasingly adopted as a local adaptation measure to protect vulnerable populations during heat events. This study aims to develop and test a SWOT–CAME analytical framework to evaluate and compare the maturity, equity, and implementation logic of urban climate refuge networks in three European cities with contrasting climates and governance traditions: Barcelona, Amsterdam, and Copenhagen. A qualitative multiple-case design is combined with a transparent indicator set (coverage, accessibility, and typology mix) derived from official municipal sources and planning documents. Results show differentiated pathways: Barcelona represents an institutionalized network model; Amsterdam illustrates an emerging coordinated public-health approach; and Copenhagen reflects an ecosystem-based orientation where green–blue infrastructure provides substantial passive cooling capacity but requires clearer heat-specific operational protocols. The discussion highlights the need for hybrid adaptation strategies that combine nature-based solutions with operational governance and targeted support for vulnerable groups. The paper concludes with a transferable framework for cities seeking to integrate climate refuges into resilience and climate-justice agendas.

Keywords: urban climate refuges; climate shelters; thermal stress; urban resilience; climate justice; nature-based solutions; blue–green infrastructure; New European Bauhaus; SWOT–CAME

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1. Introduction

Europe is warming faster than any other continent, and recent assessments show that heat extremes are becoming more frequent and more intense, with direct consequences for urban safety and public health [1]. In cities, these trends are amplified by the urban heat island effect: dense built-up areas, limited ventilation, and insufficient vegetation increase heat storage and reduce nocturnal cooling, prolonging thermal stress and exposure [2]. The health burden associated with heat is already measurable and large. During the summer of 2022, an estimated 61,672 heat-related deaths occurred across 35 European countries, equating to roughly 945 heat-related deaths per summer week on average [3]. In 2023, heat-related mortality remained exceptionally high, with an estimated 47,690 deaths

(approximately 730 per summer week on average), reinforcing that extreme heat has become a persistent public health stressor rather than an episodic anomaly [4].

Beyond total mortality burdens, attribution research indicates that a considerable fraction of heat-related deaths is already linked to anthropogenic warming. Vicedo-Cabrera et al. quantify the burden attributable to recent human-induced climate change across multiple settings and show that present-day heat mortality is partly climate-change-driven rather than exclusively due to natural variability [5]. In the Netherlands, national climate–health reporting also highlights a substantial attributable component of heat-related mortality, translating attribution evidence into policy urgency and reinforcing the need for actionable local adaptation [6]. Together, these findings support two key implications for urban research: extreme heat is a measurable, ongoing public health hazard; and adaptation should be understood as near-term health protection as well as a long-term resilience objective [5,6].

In this context, urban climate refuges have emerged as a practical and scalable municipal response. In this paper, an urban climate refuge is defined as a safe and accessible indoor or outdoor space that provides thermal relief during heat events while maintaining ordinary social functions, combining thermal performance with usability and social acceptability [7]. Barcelona offers a prominent example of institutionalisation at scale: the city reports more than 350 climate shelters and indicates that 98% of residents have access within a 10-min walk (and 68% within 5 min), integrating indoor facilities (such as libraries and civic centres) and outdoor spaces (such as parks and school yards) [8,9]. Amsterdam represents a distinct policy pathway, emphasising co-ordination, communication, and the protection of vulnerable groups through a dedicated heat plan embedded in wider heat–health governance [10].

Despite rapid growth in municipal heat measures, academic assessment of refuge networks still faces a clear gap. Many studies describe individual interventions (cooling centres, green spaces, shading, canopy strategies), but fewer provide transparent and comparable approaches to evaluate how a city-wide refuge network performs as a socio-technical system, including equity intent, activation protocols, and monitoring maturity [7,11]. Cross-city comparisons are also frequently weakened by inconsistent terminology, different national definitions of heat events, and non-comparable indicators such as absolute counts of shelters without adjustment for population, area, or spatial distribution [11,12]. These limitations are particularly relevant for comparative visualisations and benchmarking, because absolute numbers can be misleading when cities differ in population size, urbanised area, density, hazard regimes, and vulnerability profiles.

Accordingly, this study prioritises indicators that can be normalised across cities (e.g., refuges per 100,000 inhabitants; refuges per km^2 of municipal administrative area; and proximity-based coverage targets), complemented by spatially explicit reporting of coverage logic where data allow [12]. We avoid absolute shelter counts for cross-city comparison and interpret results in relation to baseline climatic context (using Köppen–Geiger climate classification as a shared descriptor), rather than treating hazard regimes as interchangeable [13].

This study addresses these challenges by introducing an operational, equity-oriented evaluation of urban climate refuge networks in Barcelona, Amsterdam, and Copenhagen. The selection of cases is justified by contrasting climatic contexts and governance traditions while remaining comparable within a European adaptation discourse. Climate classification provides a consistent language for contextualising baseline climatic differences without conflating hazard frequency with governance performance [13]. Methodologically, we combine a SWOT–CAME framework with explicit reporting of data sources and network attributes (typology mix, accessibility intent, activation readiness, and monitoring signals), prioritising interpretable indicators that can be normalised (per capita and spatial coverage expressions) to avoid misleading conclusions based on absolute counts.

1.1. Theoretical Framework

1.1.1. Urban Climate Refuges as a Health-Protective Urban System

Urban heat risk is not determined solely by temperature. It emerges from the interaction between hazard intensity and duration, exposure (time spent in hot environments), sensitivity (age, chronic disease, housing conditions), and adaptive capacity (access to cooling, information, mobility, and social support) [2]. This framing is consistent with heat–health action planning, which emphasises preparedness, coordinated response, risk communication, and targeted protection of vulnerable groups as key elements of effective heat governance [14]. Recent European assessments also show that surveillance, evaluation, and preparedness capacities remain uneven, limiting systematic learning and evidence-based scaling of interventions across cities [12]. Climate refuges can be conceptualised as distributed exposure-reduction infrastructure embedded into heat–health response systems, complementing household-level strategies that may be inequitable, energy-intensive, or inaccessible to vulnerable groups [11,14].

1.1.2. Definition and Typology: Establishing Consistent Terminology

An urban climate refuge is defined as a safe, accessible, and socially usable space that provides thermal relief during heat events while retaining its ordinary function. This definition integrates two inseparable dimensions: thermal performance (reduction in heat exposure) and usability (familiarity, proximity, acceptability, and operational accessibility) [7]. Two main typologies are distinguished:

Indoor urban climate refuges include publicly accessible buildings that offer cooler conditions through passive measures and/or mechanical cooling, such as libraries, civic/community centres, museums, and schools. Their effectiveness depends on operational activation: opening hours aligned with alerts, clear wayfinding, drinking water availability, staffing protocols, and outreach to priority groups. Evidence reviews show that cool indoor spaces are not sufficient on their own; effectiveness is shaped by barriers to access, communication, and uptake among those most at risk [11].

Outdoor and semi-outdoor urban climate refuges include shaded parks, courtyards, arcades, tree-lined streets, and public spaces supported by cooling microclimates. Thermal relief in these areas is achieved through shade, evapotranspiration, and ventilation, while water-related cooling can strengthen comfort depending on local design and climatic conditions. Performance varies with canopy configuration, irrigation, wind regimes, and background climate [15]. To address ambiguity, this study treats “cooling centres”, “climate shelters”, and “natural climate shelters” as operational labels or subtypes within the broader concept of urban climate refuges, and uses “refuge” consistently.

Figure 1 provides a synthetic schema of the main urban climate refuge typologies and their relationship to the operational readiness dimensions coded in this study (see Table 3).

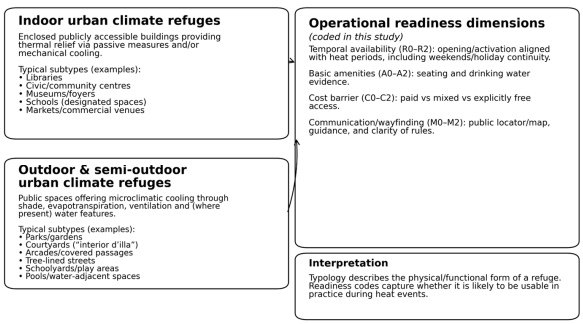
Indoor urban climate refuges
Enclosed publicly accessible buildings providing thermal relief via passive measures and/or mechanical cooling.
Typical subtypes (examples):
• Libraries
• Civic/community centres
• Museums/foyers
• Schools (designated spaces)
• Markets/commercial venues
Outdoor & semi-outdoor urban climate refuges
Public spaces offering microclimatic cooling through shade, evapotranspiration, ventilation and (where present) water features.
Typical subtypes (examples):
• Parks/gardens
• Courtyards ("interior d'illa")
• Arcades/covered passages
• Tree-lined streets
• Schoolyards/play areas
• Pools/water-adjacent spaces
Operational readiness dimensions
(coded in this study)
Temporal availability (R0–R2): opening/activation aligned with heat periods, including weekends/holiday continuity.
Basic amenities (A0–A2): seating and drinking water evidence.
Cost barrier (C0–C2): paid vs mixed vs explicitly free access.
Communication/wayfinding (M0–M2): public locator/map, guidance, and clarity of rules.
Interpretation
Typology describes the physical/functional form of a refuge. Readiness codes capture whether it is likely to be usable in practice during heat events.

Figure 1. Synthetic typology schema linking the main urban climate refuge typologies (indoor vs. outdoor/semi-outdoor, with indicative subtypes) to the operational readiness dimensions coded in this study: temporal availability (R0–R2), basic amenities (A0–A2), cost barrier (C0–C2), and communication/wayfinding (M0–M2) (see Table 3).

1.1.3. Climate Justice, Vulnerability, and Equitable Access as Evaluative Dimensions

Heat vulnerability is socially and spatially uneven. Differences in housing quality, neighbourhood greenery, mobility, health status, income, and social support shape who is exposed, who is harmed, and who can access protection [2]. As a result, refuge networks should be evaluated through a climate-justice lens that considers distributional equity (where refuges are located and who benefits), procedural inclusion (whether communities are reached and can shape interventions), and recognition (whether diverse barriers and needs are addressed). Scholarship on urban heat justice emphasises that adaptation benefits can mirror broader inequalities and that heat adaptation may unintentionally reinforce disparities without explicit equity objectives and monitoring [16]. Evidence-oriented resilience perspectives similarly warn that adaptation must be designed to avoid leaving behind those most exposed or least able to adapt [16,17].

Operationalising equity in refuge networks entails measurable criteria such as proximity targets, barrier-free accessibility, temporal availability aligned with alerts, multilingual and culturally appropriate communication, and partnerships with health and community organisations [14,17]. In comparative terms, this implies prioritising indicators that reflect access and usability for vulnerable groups, rather than relying on site counts alone.

1.1.4. Blue–Green Infrastructure and Measurable Cooling Outcomes

Nature-based approaches are widely promoted for mitigating urban heat, yet scientific rigour requires linking interventions to measurable cooling and health-relevant outcomes. Key mechanisms include shading (reducing radiant load), evapotranspiration (affecting local air temperatures and comfort), and improved ventilation patterns. Systematic syntheses report that urban green spaces can lower temperatures, though effect sizes vary substantially across vegetation types and contexts; such variability supports treating blue–green interventions as design- and context-specific rather than universally effective [15]. This evidence motivates performance-oriented indicators for refuge research, including air and surface temperature differentials (ΔTa, ΔTs), thermal comfort indices, shade availability at critical hours, and population-weighted accessibility to cooled or shaded spaces [13,15].

A hybrid adaptation logic emerges from this evidence: ecosystem-based cooling can reduce baseline exposure and improve everyday comfort, while operationally activated indoor refuges provide acute protection during extreme events, especially for vulnerable groups [11,14,15].

1.1.5. Methodological Challenges in Evaluating Refuge Network Effectiveness

Evaluating climate refuges is inherently multi-dimensional. A refuge may be thermally adequate but underused; well used but inaccessible to vulnerable groups; or adequate during moderate heat but insufficient during extremes due to limited capacity or restrictive opening hours [7,11]. Comparability is further complicated by differing national definitions of heat events and uneven availability of official inventories, activation protocols, and monitoring outputs. European assessments of surveillance and preparedness confirm that evaluation practices remain inconsistent across contexts, underscoring the need for transparent data sourcing and explicit methodological choices in comparative studies [12]. For cross-city evaluation, this justifies using normalised indicators (per capita and spatial coverage logic) and clearly separating governance maturity from hazard intensity.

1.1.6. Analytical Lens: Why SWOT–CAME Is Appropriate for Refuge Networks

Climate refuge networks function as socio-technical systems combining spatial assets (buildings, parks, shade, blue–green infrastructure) with governance and service activation (plans, alerts, staffing, communication, partnerships). SWOT analysis provides

a systematic method for synthesising internal strengths/weaknesses and external opportunities/threats and has been theoretically reviewed as a strategic analysis approach relevant across planning contexts [18]. CAME extends SWOT by translating diagnosis into action categories—correct weaknesses, address threats, maintain strengths, and exploit opportunities—supporting a practical diagnosis-to-action pathway [19]. In this paper, SWOT–CAME is embedded in transparent source extraction and complemented with operational network attributes (activation readiness, typology mix, equity intent, monitoring signals), supporting robust comparison across Barcelona, Amsterdam, and Copenhagen [18,19].

2. Materials and Methods

2.1. Study Design

This study applies a comparative, evidence-traceable design to evaluate urban climate refuge networks as socio-technical systems combining spatial assets (indoor and outdoor refuges) with activation and service protocols (opening times, accessibility provisions, communication, and targeted safeguarding). The analytical workflow integrates: (i) structured evidence extraction from official and institutional sources; (ii) a harmonised indicator framework with explicit normalisation rules for cross-city comparability; (iii) an operational readiness coding scheme to assess "availability in practice" beyond nominal existence; and (iv) a SWOT–CAME procedure to translate diagnosis into actionable strategy categories. Table 1 summarises the provenance of all primary sources and extracted variables; Table 2 defines the indicator framework and normalisation logic; and Table 3 reports the coding scheme used to assess typology and operational readiness.

Table 1. Data sources, provenance, and extracted variables.

City	Source Type	Source/Owner	Variables Extracted (Examples)
Barcelona	Municipal news/programme page	Ajuntament de Barcelona (Info Barcelona) [8]	Network size (353), coverage shares (98% ≤10 min; 68% ≤5 min), examples of indoor/outdoor typologies, eligibility framing
Barcelona	Municipal policy/SDG page	Ajuntament de Barcelona (2030 Agenda) [9]	Network scale (~400), comfort set-points (26 °C summer indoors/21 °C winter indoors), typology list, August opening counts, micro-shelter initiative
Barcelona	Open data catalogue entry	https://opendata-ajuntament.barcelona.cat/en/api-cataleg (accessed on 17 December 2025)	Existence of published inventory dataset and update frequency
Barcelona	Academic PDF	https://www.uab.cat/web/uab-mobility-plan-1345796334967.html (accessed on 17 December 2025)	Stated municipal target: universal ≤5-min access by 2030 (as reported)
Amsterdam	Municipal heat plan/health governance docs	Municipality of Amsterdam. Amsterdams Hitteplan 2024 (Amsterdam Heat Plan 2024, PDF) [10]	Heat alert protocols, refuge/cooling centre typologies, vulnerable group targeting, coordination mechanisms
Amsterdam	Project record/web tool (cool places)	Open Research Amsterdam. 'Find Your Cool' map (Koele Plekken Checker) [20]	Cooling-place typologies, user-facing access logic, tool-based guidance
Copenhagen	Municipal climate adaptation/heat guidance	City of Copenhagen. Copenhagen Climate Adaptation Plan—Short Version (2011, PDF) [21]	Heat island framing; cooling measures (water, shade, air circulation); planning precautions
Copenhagen	Municipal committee record	City of Copenhagen (Teknik-og Miljøudvalget). Indsats mod varmeøer i København (meeting record) [22]	Monitoring/data gaps; integration into strategies; mapping/monitoring roadmap

Table 2. Indicator framework and normalisation logic.

Domain	Indicator	Definition	Unit	Normalisation Rule (Required)	Data Inputs	Comparable Across Cities?
Supply	Refuge provision (population-adjusted)	Number of designated refuges relative to resident population	refuges/100,000 residents	Divide by population; report year of population baseline	Inventory count; population	Yes (if counts & population available)
Supply	Refuge provision (area-adjusted)	Number of designated refuges relative to municipal area	refuges/km^2	Divide by area within comparable boundary definition	Inventory count; area	Yes (if boundary definitions align)
Access	Walking-time coverage	Share of residents within a stated walking-time threshold to nearest refuge	% residents	Use identical threshold definition (e.g., 10-min walk); avoid mixing thresholds	Published coverage metric or computed isochrones	Conditional (only if same threshold published/computable)
Equity	Vulnerability-weighted access	Access metric weighted by vulnerability proxy	index or %	Weight access by vulnerability layer; report layer definition	Vulnerability dataset; access	Conditional (data availability)
Typology	Typology mix	Share of refuges by typology class (indoor/outdoor; subtypes)	% of refuges	Use consistent typology dictionary (Table 3)	Inventory with labels	Conditional
Readiness	Availability index	Composite of opening alignment, basic amenities, and cost barrier	ordinal or score	Apply identical scoring rubric (Table 3)	Opening rules; amenities; cost	Yes (if evidence available)
Seasonal robustness	August/weekend continuity	Share of refuges open at weekends and/or August	% refuges	Report same seasonal window and days	Opening schedules	Conditional

Dimension	Codes	Operational definition	Minimum evidence required
Typology (primary)	Indoor refuge	Enclosed public/private-access space intended to provide thermal relief during heat events (passive and/or mechanically cooled)	Official designation + address/location
Typology (primary)	Outdoor/semi-outdoor refuge	Shaded or cooled public space (parks, courtyards, arcades, schoolyards) where microclimate reduces heat exposure	Official designation + location
Typology (secondary examples)	Library; civic/community centre; museum foyer; market; shopping centre; school facility; park/garden; courtyard ("interior d'illa"); play-area cooling space; pool	Subtype assigned when explicitly stated in source	Explicit typology label in source
Readiness: temporal	R0–R2	R0: no clear opening information; R1: opening times published but not aligned with heat periods/weekends; R2: explicitly aligned with heat season/alerts and includes weekends or extended hours	Public opening times and/or activation protocol
Readiness: amenities	A0–A2	A0: no evidence of seating/water; A1: partial (either seating or water); A2: both seating and drinking water confirmed	Programme description or facility info
Readiness: cost barrier	C0–C2	C0: paid access; C1: mixed/conditional; C2: free access (explicit)	Fee policy statement
Readiness: communication	M0–M2	M0: no public locator/wayfinding; M1: list exists but limited; M2: public map/locator and basic guidance available	Public-facing map/website and guidance

Table 3. Typology dictionary and operational readiness coding scheme.

Dimension	Codes	Operational Definition	Minimum Evidence Required
Typology (primary)	Indoor refuge	Enclosed public/private-access space intended to provide thermal relief during heat events (passive and/or mechanically cooled)	Official designation + address/location
Typology (primary)	Outdoor/semi-outdoor refuge	Shaded or cooled public space (parks, courtyards, arcades, schoolyards) where microclimate reduces heat exposure	Official designation + location
Typology (secondary examples)	Library; civic/community centre; museum foyer; market; shopping centre; school facility; park/garden; courtyard ("interior d'illa"); play-area cooling space; pool	Subtype assigned when explicitly stated in source	Explicit typology label in source

Table 3. *Cont.*

Dimension	Codes	Operational Definition	Minimum Evidence Required
Readiness: temporal	R0–R2	R0: no clear opening information; R1: opening times published but not aligned with heat periods/weekends; R2: explicitly aligned with heat season/alerts and includes weekends or extended hours	Public opening times and/or activation protocol
Readiness: amenities	A0–A2	A0: no evidence of seating/water; A1: partial (either seating or water); A2: both seating and drinking water confirmed	Programme description or facility info
Readiness: cost barrier	C0–C2	C0: paid access; C1: mixed/conditional; C2: free access (explicit)	Fee policy statement
Readiness: communication	M0–M2	M0: no public locator/wayfinding; M1: list exists but limited; M2: public map/locator and basic guidance available	Public-facing map/website and guidance

2.2. Case Selection and Climatic Context

The analysis focuses on three European cities selected to enable comparison across distinct governance traditions and climatic baselines while remaining within a shared policy discourse on heat–health adaptation. Climatic context is treated as background exposure rather than a proxy for governance performance. Where required, climate classification is reported using Köppen–Geiger letter codes to avoid ambiguous descriptors (e.g., "Mediterranean" versus "temperate oceanic") and to make cross-case interpretation transparent.

2.3. Data Sources and Evidence Extraction

Primary evidence was collected from official municipal webpages, public policy documents, and (where available) published inventories and programme descriptions of climate refuges. For each city, sources were screened and extracted using standardised evidence register (integrated in Table 1) recording: title/owner, URL, date accessed, document type, and the specific variables extracted (e.g., inventory size, typology labels, opening rules, eligibility conditions, comfort requirements, and stated access targets). This approach improves reproducibility and enables readers to trace each empirical statement to a verifiable origin.

For Barcelona, official municipal communications provide headline network metrics and operational definitions, including reported coverage within 5- and 10-min walking thresholds and programme descriptions of indoor/outdoor refuge types.

2.4. Refuge Typology Classification and Terminology Control

To ensure terminological consistency, all spaces are classified under the umbrella term "urban climate refuges", defined as safe, accessible spaces providing thermal relief during heat events while maintaining ordinary social functions. Operational labels used by cities (e.g., "cooling centres", "climate shelters", "natural climate shelters") are treated as subtypes or programme labels and mapped into a consistent typology dictionary (Table 3). Typologies are coded at minimum into indoor and outdoor/semi-outdoor categories, with optional sub-codes (e.g., libraries, civic centres, parks, schoolyards, commercial venues) when sources provide sufficient detail.

2.5. Operational Readiness and Usability Coding

Availability during heat events depends not only on physical presence but on activation and usability. Therefore, a readiness coding scheme was applied to capture whether a refuge is likely to function as intended during heat alerts. Coding dimensions include temporal availability (weekday/weekend and seasonal continuity), basic amenity provision (seating, drinking water), cost barriers (free versus paid access), and operational clarity

(publicly communicated rules and wayfinding). Readiness codes, evidence requirements, and examples are standardised in Table 3.

2.6. Indicator Framework and Normalisation Logic

Cross-city comparison is sensitive to differences in population size, city area, density, and hazard regimes. To avoid misleading inference from absolute counts, indicators are normalised using explicit rules (Table 2). Core indicators include per capita and per-area supply (e.g., refuges per 100,000 residents; refuges per km^2), and access/coverage metrics where cities publish consistent thresholds (e.g., share of residents within a defined walking time). Where an indicator cannot be computed consistently across all cases due to data gaps, it is reported qualitatively and flagged as non-comparable, rather than forcing an imputed quantitative comparison.

Multi-Source Dataset Uncertainty and Uncertainty Propagation

To improve clarity and reproducibility, this subsection explains how and why the study indicators were selected and how uncertainty in multi-source evidence can propagate through the analytical workflow. The indicator set was designed to support a **traceable cross-city system evaluation** of urban climate refuge networks while avoiding pseudo-precision when inventories or definitions are not harmonised. Data provenance and extracted variables are documented in Table 1, the indicator framework and normalisation rules are defined in Table 2, and the typology and operational readiness coding rubric is standardised in Table 3.

Indicator selection rationale and derivation. Candidate indicators were compiled from (i) core dimensions implied by the refuge-network concept (supply, access, typology, readiness, and equity), (ii) variables that could be consistently extracted from the registered evidence base (Table 1), and (iii) the requirements of cross-city comparison under explicit normalisation constraints (Table 2).

We retained indicators only when they satisfied five screening criteria:

Alignment with study objectives. Indicators had to map directly onto the study's evaluative aims: (a) network structure and composition (typology); (b) operational readiness/usability during heat events; (c) governance activation and learning capacity; and (d) equity-relevant access constraints.

Measurability and traceability. Indicators were required to be supported by verifiable sources and auditable coding rules (Table 1), avoiding metrics that depend on undocumented assumptions or non-transparent procedures.

Cross-city comparability (definitional consistency). Because municipal labels and categories differ, indicators were prioritised when they could be expressed using consistent definitions and evidence requirements, including the shared typology/readiness dictionary (Table 3).

Normalisation feasibility. We prioritised indicators that can be normalised using common denominators (population, area) or comparable access thresholds, in line with Table 2. Metrics that could not be normalised without strong imputation were not used for quantitative benchmarking.

Equity sensitivity. To avoid equating nominal designation with real usability, we prioritised indicators and codes that can surface equity-relevant barriers, especially temporal continuity, cost barriers, basic amenities, and communication/wayfinding, as operationalised by the readiness dimensions in Table 3.

This screening protocol also guided the exclusion of alternative metrics when they (i) relied on non-equivalent definitions across cities, (ii) mixed incompatible time windows (e.g., year-round vs. seasonal activation) without transparent adjustment, (iii) required imputation to fill inventory gaps, or (iv) risked biasing comparisons by privileging cities with more comprehensive

public reporting rather than better-performing systems. In such cases, evidence was retained as contextual qualitative input rather than converted into rankable indicators.

Multi-source dataset uncertainty and uncertainty propagation. Because the study relies on heterogeneous evidence layers (municipal programme pages, policy documents, tool-based maps, and secondary reports), uncertainty arises not only from measurement error but also from differences in **completeness, definitions, and timing**. First, **inventory completeness uncertainty** affects whether "refuge provision" can be treated as a countable network variable: some cases provide consolidated inventories while others provide partial listings or user-facing guidance layers that may under-represent supply or omit attributes needed for harmonised coding (Table 1).

Second, **definition and boundary uncertainty** affects comparability when operational labels and inclusion rules differ, which can influence area- and population-normalised indicators (Table 2).

Third, **temporal uncertainty** arises when datasets refer to different years, seasons, or operational states (e.g., summer-only activation or August closures), such that nominal designation may not match functional availability during peak exposure.

These uncertainties can **propagate through the workflow**: classification choices (what qualifies as a refuge and how typology/readiness are coded using Table 3) determine what enters the indicator set; normalisation choices (denominators, thresholds, and provenance in Table 2) shape the magnitude and meaning of reported indicators; and synthesis (SWOT → CAME) can amplify upstream bias if uncertainty is not made explicit.

To manage propagation risk, we (i) document evidence provenance via the source register (Table 1), (ii) restrict quantitative benchmarking to definitionally consistent indicators with explicit normalisation rules (Table 2), and (iii) apply standardised coding requirements for typology and readiness (Table 3), treating non-harmonised evidence as contextual rather than rankable.

2.7. SWOT–CAME Procedure

SWOT synthesis was conducted after evidence extraction and indicator compilation. Strengths and weaknesses represent internal attributes of the refuge system (e.g., typology diversity, activation protocols, monitoring maturity). Opportunities and threats represent external drivers (e.g., increasing heat extremes, seasonal closures, resource constraints, or reliance on paid facilities). CAME translation (Correct, Address, Maintain, Exploit) was then used to convert SWOT findings into action-oriented strategies aligned with governance and implementation levers. To limit subjectivity, each SWOT entry was grounded in at least one traceable evidence item recorded in Table 1. Figure 2 formalises the transferable framework as an eight-step workflow from evidence extraction to SWOT → CAME strategy translation

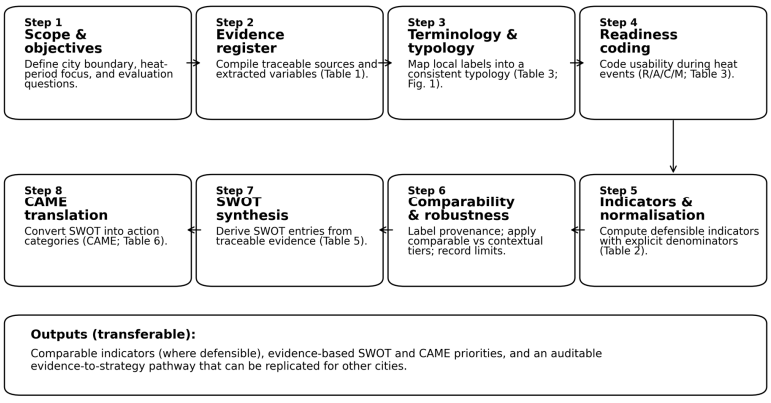
Step 1
Scope & objectives
Define city boundary, heat-period focus, and evaluation questions.
Step 2
Evidence register
Compile traceable sources and extracted variables (Table 1).
Step 3
Terminology & typology
Map local labels into a consistent typology (Table 3; Fig. 1).
Step 4
Readiness coding
Code usability during heat events (R/A/C/M; Table 3).
Step 5
Indicators & normalisation
Compute defensible indicators with explicit denominators (Table 2).
Step 6
Comparability & robustness
Label provenance; apply comparable vs contextual tiers; record limits.
Step 7
SWOT synthesis
Derive SWOT entries from traceable evidence (Table 5).
Step 8
CAME translation
Convert SWOT into action categories (CAME; Table 6).
Outputs (transferable):
Comparable indicators (where defensible), evidence-based SWOT and CAME priorities, and an auditable evidence-to-strategy pathway that can be replicated for other cities.

Figure 2. Transferable SWOT–CAME framework: eight-step evidence-to-strategy workflow for urban climate refuge network evaluation.

2.8. Reliability Checks and Limitations

Two reliability safeguards were applied. First, all empirical claims were cross-checked against their registered source entries (Table 1). Second, indicators were only compared quantitatively when the same definition and normalisation rule could be applied across cases (Table 2). Key limitations include uneven transparency of municipal inventories and opening protocols, and the potential mismatch between nominal refuge designation and real-world use under extreme heat. Where primary inventories were not technically retrievable in this environment, only headline metrics from official communications were used, and the limitation is stated explicitly.

3. Results

3.1. Evidence Base, Traceability, and Comparability Rules

Across the three cases, the depth of *network-inventory evidence* (i.e., a consolidated list of refuge locations and attributes) is uneven, which directly constrains fully harmonised quantitative benchmarking. Barcelona provides a clearly institutionalised municipal climate-shelter programme with published proximity coverage metrics and programme descriptions [8,9]. Amsterdam provides a detailed Heat Plan (2024) specifying triggers, roles, target groups, and an annual update cycle [23], but does not consistently provide a single consolidated, downloadable citywide refuge inventory in the core sources reviewed [20,24]. Copenhagen provides long-term adaptation framing that explicitly recognises urban heat islands and recommends cooling precautions (water, shade, and air circulation) [21], while a later committee record identifies data and strategic integration gaps as constraints and prioritises citywide mapping/monitoring as the enabling step [22].

To prevent misleading cross-city inference, results are reported under two comparability tiers.

Tier 1 (comparable): indicators are compared only when definitions and denominators are traceable and consistent (e.g., per capita normalisation using official population baselines).

Tier 2 (contextual, not rankable): city-reported metrics (e.g., proximity coverage targets) are reported transparently but not used for ranking when equivalent metrics are not available for all cities.

3.2. Barcelona: Programme Scale, Access Coverage, Temporal Robustness, and Equity Signals

Programme scale and reported coverage. Barcelona reports a large municipal climate-shelter network (over 350 shelters) and states that 98% of residents have access to a climate shelter within a 10-min walk, and 68% within a 5-min walk [8]. The programme explicitly combines indoor refuges (e.g., libraries, community centres, museums) and outdoor/semi-outdoor refuges (parks, gardens, school playgrounds, and inner-block courtyards) [8,9].

Change over time (access intensification). In 2023, Barcelona reported 97% within 10 min and 58% within 5 min, alongside a stated ambition to expand five-minute access [23]. By mid-2024, reported five-minute access increased to 68% [8].

Normalised supply (within-case scaling). Using the reported network size for summer 2024 (353 shelters) [8] and the official municipal baseline for Barcelona (population and surface area) [25], Barcelona's supply can be expressed transparently as:

- 20.6 refuges per 100,000 residents, and
- 3.48 refuges per km^2.

These values support reproducible scaling within the case; they are not used as cross-city performance scores unless comparable inventories exist for all cases.

Temporal robustness (nominal vs. open network). Operational continuity differs from nominal designation: reporting based on municipal information indicates that on Sundays in August (when many facilities close), the 10-min access coverage drops to 89% [26]. This

highlights that "effective protection" depends on opening rules during peak-risk periods (weekends/holiday weeks), not only on the number of designated sites.

Equity signal (vulnerability framing). Barcelona also provides research-facing material that frames shelter access for heat-vulnerable groups, supporting the interpretation that equity considerations are being operationalised (at least partially) through access reporting [27].

3.3. Amsterdam: Governance Maturity, Activation Logic, and Tool-Based Cooling Guidance

Governance and activation logic. The Amsterdam Heat Plan 2024 frames heat risk in relation to health impacts and the urban heat island effect, and sets out a co-ordinated response involving the municipality, GGD, GHOR and societal organisations [10]. The plan is explicitly linked to activation under the National Heat Plan and includes an annual evaluation/update cycle [10].

Vulnerability targeting. The plan identifies priority groups for safeguarding and frames vulnerability in a way consistent with heat–health governance approaches (sensitivity and limited adaptive capacity) [10]. This indicates high *activation readiness* at governance level (roles, triggers, communication, and learning loop), even when spatial inventories are less consolidated than Barcelona's.

Heatwave definition clarity (comparability implication). Dutch national documentation distinguishes between plan activation and the retrospective meteorological definition of an "official heatwave"; the latter is commonly defined as $\geq$5 consecutive days $\geq$25 °C in De Bilt, of which $\geq$3 days exceed 30 °C [28]. This supports the methodological decision to avoid direct cross-city "heatwave frequency" comparisons when definitions differ by country.

Inventory limitations for network quantification. Amsterdam also provides tool-based guidance to residents (e.g., "Find Your Cool/Koele Plekken Checker"), described as a map/app to locate cooler places during heat events [20,24]. However, within the reviewed sources, this does not appear as a single, standardised, downloadable refuge inventory comparable to Barcelona's network framing, limiting point-based, normalised supply and coverage computation across all three cases without introducing non-traceable assumptions.

3.4. Copenhagen: Structural Cooling Paradigm and a Documented Monitoring Gap

Policy framing for UHI and cooling precautions. Copenhagen's Climate Adaptation Plan (short version) recognises the heat island effect and anticipates that more frequent and intense heatwaves may pose challenges; it recommends that renewal and development incorporate precautions against high temperatures, including water, shade, and air circulation [21]. This aligns with a long-term blue–green and urban-form cooling paradigm in which public-space design can provide distributed outdoor "refuge-like" relief.

Evidence infrastructure barrier (2024 committee record). A later municipal committee record (August 2024) states that heat islands have not previously been integrated across strategies and action plans and that available heat-island data (e.g., satellite-based) have limitations; the document prioritises mapping, monitoring, and analysis to enable targeted interventions and future strategic integration [22]. This is a key result differentiator: evidence and monitoring capacity is framed as the prerequisite for targeted UHI action.

3.5. Cross-Case Comparison Using Traceable, Non-Misleading Indicators

Because the evidence base does not provide harmonised, downloadable refuge-point inventories for all three cities, cross-case quantitative benchmarking is constrained to traceable indicators and governance attributes, without forcing pseudo-precision (Table 4).

Table 4. Cross-case results summary with provenance labels.

Dimension	Barcelona	Amsterdam	Copenhagen
Institutionalisation form	Climate shelters programme with published access metrics [8,23]	Heat Plan with specified roles/triggers and annual cycle [10]	Adaptation plan frames UHI + committee flags integration/data gap [21,22]
Published proximity coverage	98% ≤10 min; 68% ≤5 min (2024) [8]	Not published as unified refuge-network coverage in reviewed core sources [20,24]	Not published as refuge-network coverage metric [22]
Headline network size	353 shelters (summer 2024) [8]	Not consolidated as a refuge inventory in reviewed sources	Not consolidated as a refuge inventory
Normalised supply (computed)	20.6/100 k; 3.48/km^2 (computed from official baseline) [25]	Not computable without consolidated inventory	Not computable without consolidated inventory
Temporal robustness signal	Sunday/August 10-min access drops to 89% [26]	Governance cycle supports preparedness/learning [10]	Monitoring/data barrier explicitly stated [22]

3.6. SWOT Results Grounded in Evidence

SWOT inputs were derived from Sections 3.2–3.5, separating internal attributes (Strengths/Weaknesses) from external drivers (Opportunities/Threats). Importantly, each entry corresponds to a traceable result and is not inferred from absolute counts alone.

3.7. CAME Results (Strategy Translation)

CAME strategies were derived by translating Table 5 into implementable action categories (Correct, Address, Maintain, Exploit), making the diagnosis-to-action pathway explicit and auditable (Table 6).

Table 5. Evidence-based SWOT synthesis by city.

City	Strengths	Weaknesses	Opportunities	Threats
Barcelona	Published proximity coverage and measurable access framing; mixed indoor–outdoor typologies [8,9,23]	Nominal vs. open-network gap during peak-risk periods (weekends/holiday season) [26]	Formalise vulnerability-weighted access reporting and prioritisation methods [27]	Reduced access during closures may disproportionately affect vulnerable residents [26]
Amsterdam	High governance readiness: triggers, roles, annual review cycle, target groups [10]	Lack of a single consolidated refuge inventory in reviewed sources limits spatial benchmarking [20,24]	Convert tool-based "cool places" into a transparent, typology-coded refuge layer aligned with the Heat Plan [10,20]	Comparability pitfalls if national heatwave definitions are treated as equivalent [28]
Copenhagen	Structural cooling paradigm (water/shade/air circulation) embedded in adaptation framing [21]	Data resolution and strategy integration gap explicitly documented [22]	Implement citywide mapping/monitoring enabling targeted interventions [22]	Rising heat risk may outpace evidence capacity if monitoring is delayed [22]

Table 6. CAME strategy outputs (derived from Table 5).

City	Correct	Address	Maintain	Exploit
Barcelona	Correct the open-network gap by strengthening weekend/holiday opening protocols and contingency staffing [26]	Address seasonal inequity risk by ensuring continuity in high-vulnerability areas during August/weekends [26,27]	Maintain measurable proximity targets and mixed typologies (indoor + outdoor) [8,23]	Exploit equity-oriented reporting by institutionalising vulnerability-weighted indicators for investment decisions [27]
Amsterdam	Correct evaluation/benchmarking limits by publishing a consolidated refuge layer (typology + access rules) under Heat Plan governance [10,20,24]	Address fragmentation by creating shared data governance across actors for heat protection services [10]	Maintain clear triggers, roles and annual learning cycle [10]	Exploit existing tools to integrate indoor refuges and targeted routes for vulnerable groups during alerts [20,24]
Copenhagen	Correct the evidence deficit through fine-resolution mapping/monitoring and citywide analysis [22]	Address strategy integration by embedding heat-island action into municipal plans with measurable indicators and accountability [22]	Maintain structural cooling emphasis (water/shade/air circulation) in renewal and public-space design [21]	Exploit monitoring roadmap to evaluate pilots and scale effective interventions [22]

3.8. Summary of Key Comparative Findings

Three cross-cutting results emerge robustly from traceable sources:

(i) Barcelona provides the most explicit programme institutionalisation and access reporting, including proximity coverage and typology diversity [8,23].
(ii) Amsterdam provides the most explicit governance activation maturity (roles, triggers, annual evaluation), even if the refuge network is not published as a consolidated inventory in the reviewed material [10].
(iii) Copenhagen highlights a critical evidence/monitoring constraint, positioning mapping and monitoring as the prerequisite for targeted UHI action and integration into strategies [22].

3.9. Sensitivity and Robustness Checks

To address sensitivity to definitions, data gaps, and comparability pitfalls, we applied the following robustness logic:

Normalisation sensitivity (counts vs. denominators). We do not compare absolute shelter counts across cities because differences in municipal area, population, and the presence/absence of consolidated inventories can produce misleading rankings. Barcelona's shelter count is normalised only within-case using official denominators [25], and equivalent metrics are not computed for Amsterdam and Copenhagen without traceable inventories.

Metric provenance sensitivity (reported vs. computed). Where a metric is *municipality-reported* (e.g., Barcelona 5/10-min access shares), it is labelled as such and not treated as directly comparable unless a functionally equivalent metric is available for all cities. This avoids mixing reported coverage with modelled coverage without explicit labelling [8,23].

Threshold sensitivity (heatwave definitions). Because national heatwave definitions differ (e.g., Dutch meteorological definition tied to De Bilt [28]), and Danish and broader European indicator practices use different thresholds/indices, we do not benchmark "heatwave frequency" as an outcome metric across cases. Instead, we benchmark governance and network attributes (institutionalisation, activation readiness, monitoring maturity), which are conceptually transferable [10,21,22,28].

Evidence completeness sensitivity (inventory availability). Amsterdam's tool-based "cool places" approach and Copenhagen's monitoring-gap framing are treated as evidence of policy and governance pathways, not as equivalent to a consolidated refuge inventory. Where inventories are absent or fragmented, results are restricted to traceable governance and qualitative network attributes, and the limitations are explicitly stated [20,22,24].

Interpretation sensitivity (hazard vs. governance). Climatic baseline differences can confound interpretation if not separated from governance performance. We therefore interpret results as differences in network maturity, governance readiness, and monitoring capacity, rather than as direct performance under equivalent hazard regimes [21,22].

These checks strengthen internal validity and directly respond to reviewer concerns about comparability, provenance, and methodological transparency.

Uncertainty propagation across the workflow (classification → normalisation → synthesis). In addition to definition and comparability sensitivity, we explicitly consider how multi-source uncertainty can propagate across steps. When inventories are incomplete or not consolidated, classification and readiness coding may be biased toward what is publicly documented rather than what exists in practice; this, in turn, constrains which indicators can be computed and can shift interpretation toward governance attributes rather than spatial performance. Likewise, mixing municipality-reported coverage (e.g., published 5/10-min access shares) with computed indicators can create pseudo-comparability unless provenance is labelled and thresholds are aligned. Because these propagation pathways can affect equity-related interpretation (e.g., apparent access vs. effective access during peak-risk periods), we treat equity assessment as conditional on transparent evidence layers and avoid over-interpreting gaps as performance differences without harmonised data.

4. Discussion

From descriptive comparison to actionable system evaluation. Cross-city refuge studies often risk becoming descriptive and non-comparable when they rely on absolute counts and heterogeneous sources. This paper advances a traceable system evaluation by constraining quantitative comparison to normalised, definitionally consistent indicators and by making the SWOT → CAME pathway explicit (Tables 5 and 6), thereby converting comparative diagnosis into implementable strategy categories. In addition, the robustness logic (Section 3.9) clarifies what can be inferred from the available evidence and what cannot, preventing the analysis from drifting into ungrounded generalisations.

Dataset uncertainty is an equity-relevant methodological issue. A key implication of using multiple, heterogeneous datasets is that uncertainty is not merely statistical; it is also structural, reflecting uneven transparency, definitional ambiguity, and differences in what is recorded and published. These upstream choices can shape downstream conclusions about access, readiness, and equity, particularly when "nominal" networks are interpreted as "open" networks without consistent temporal evidence. Recent work on more reliable and equitable urban assessments emphasises that data completeness, harmonised definitions, and explicit computation steps are prerequisites for defensible equity claims. Accordingly, our findings should be read as a traceable Stage 1 system evaluation: robust for identifying governance maturity, activation readiness, and monitoring constraints, but not sufficient for causal claims or fine-grained equity ranking until harmonised inventories and uptake/usage evidence are available.

Network maturity is multi-dimensional: institutionalisation versus activation readiness. The comparative results suggest that network maturity is not a single continuum but at least a two-axis construct. Barcelona illustrates strong institutionalisation and a measurable access framing through published 5/10-min proximity metrics and a mixed indoor–outdoor programme narrative [8,23]. Amsterdam, by contrast, demonstrates strong activation readiness, characterised by explicit triggers, delineated roles, and an annual evaluation cycle [10]. These dimensions are complementary rather than interchangeable: a large programme can become operationally fragile if access drops during weekends or holiday periods—consistent with reduced Sunday/August availability signals observed for Barcelona [26]—while a governance system can remain robust even when inventories are not consolidated into a single public dataset, as in Amsterdam [10]. This distinction helps explain why headline scale does not automatically translate into reliable protection at the moment of peak exposure.

Equity requires temporal continuity as well as spatial access. Barcelona's proximity reporting provides a credible pathway to operationalise equity, particularly if extended to vulnerable groups and linked to monitoring of service continuity [27]. However, the distinction between nominal and open networks indicates that temporal continuity can itself become an equity barrier when closures coincide with peak heat exposure and when household adaptive capacity is constrained [26]. For Amsterdam and Copenhagen, fragmented inventories and limited fine-grained monitoring constrain the strength of equity claims, suggesting that equity assessment will remain partial unless data governance improves and a shared, transparent evidence layer is established [20,22,24]. In practical terms, equity cannot be inferred only from where refuges are located; it also depends on when they are reliably accessible and how access is communicated during events.

A defensible interpretation is a hybrid adaptation model. Taken together, the comparative evidence supports a hybrid logic combining (i) baseline cooling capacity (blue–green and urban-form measures, emphasised in Copenhagen's adaptation framing) [21]; (ii) event-based protection through activated indoor and outdoor refuges (aligned with Barcelona's programme logic) [8,9]; (iii) governance activation and learning loops (reflected in Amster-

dam's heat plan structure) [10]; and (iv) monitoring and evaluation capacity as an enabling condition, explicitly foregrounded in Copenhagen's 2024 record [22]. Rather than positioning these components as alternatives, the cases indicate that they reinforce one another: baseline measures reduce background vulnerability, while activated refuges and clear governance structures provide operational protection during extremes, and monitoring enables iterative improvement.

Avoiding over-claiming causality. The available evidence supports interpretation of system attributes such as institutionalisation, readiness, and monitoring maturity, but it does not support causal claims about prevented morbidity or mortality without counterfactual modelling and robust usage/uptake data. Accordingly, the appropriate staged pathway is to treat this paper as a transparent "Stage 1" system evaluation, and to position future work around integrating consistent inventories, thermal-exposure indicators, and uptake evidence in order to estimate effectiveness more directly. This staged framing preserves the value of comparative governance insights while remaining explicit about evidentiary limits.

Transferable governance lessons. The cross-case synthesis yields practical lessons that remain transferable even under imperfect data conditions. Barcelona's measurable proximity framing is transferable as an accountability device, but it should be paired with explicit temporal continuity requirements to avoid "paper access" that collapses during high-risk periods [8,23,26]. Amsterdam's governance architecture is transferable as a template for activation readiness, particularly for cities where refuge inventories are still evolving but operational clarity is achievable through triggers, roles, and review cycles [10]. Finally, Copenhagen's explicit monitoring roadmap is itself a transferable governance lesson: investment in evidence infrastructure can be an enabling intervention that makes targeted action possible, strengthens evaluation, and reduces uncertainty in subsequent decision cycles [22].

5. Conclusions

This study evaluated urban climate refuge networks as socio-technical systems rather than as shelter counts. The comparative evidence indicates that robust heat protection depends on a hybrid configuration combining measurable access, activation readiness, and monitoring capacity, while avoiding misleading benchmarking across climates with incompatible hazard definitions.

Barcelona illustrates strong programme institutionalisation through publicly communicated proximity access framing and a mixed indoor–outdoor typology [8,20]. However, the observed difference between nominal and actually open networks during weekends/holiday periods demonstrates that temporal continuity is a decisive operational dimension for effective protection and should be assessed alongside spatial proximity [26]. Amsterdam illustrates high activation readiness through clear triggers, delineated roles and responsibilities, and a recurring evaluation/update cycle embedded in the Heat Plan [10]. This indicates that governance maturity and learning loops can be transferable assets for cities building or reorganising refuge systems, even when refuge inventories are less consolidated in public documentation [20,24]. Copenhagen illustrates a structural cooling paradigm anchored in blue–green and urban-form strategies [21] and, critically, identifies monitoring and data maturity as an enabling condition for targeted heat-island action and integration into strategies [22].

Methodologically, the paper strengthens rigour by constraining quantitative comparison to traceable, normalised indicators; separating contextual city-reported metrics from comparable metrics; and making the evidence-to-strategy pathway explicit via SWOT → CAME (Tables 5 and 6). Practically, the resulting CAME priorities are clear:

correct temporal continuity gaps (Barcelona-type challenge), consolidate typology-coded refuge data layers under heat governance (Amsterdam-type opportunity), and treat mapping/monitoring as enabling infrastructure for targeted deployment and evaluation (Copenhagen-type constraint) [10,22,26].

Provides a conceptual hybrid model that integrates hazard–exposure context, baseline cooling capacity, activated refuges, and governance/monitoring feedback loops. The model is intended as a transferable framework for future research and municipal implementation, while remaining cautious about causal claims until consistent inventories, uptake evidence, and counterfactual evaluation designs are available.

Policy Recommendations

- Guarantee temporal continuity during peak-risk periods by aligning refuge opening hours with heat alerts (including weekends/holiday weeks) and establishing contingency staffing for closures. *(Correct/Address—Barcelona)* [26].
- Publish a consolidated, typology-coded refuge layer (indoor/outdoor; access rules; opening times; basic amenities) under municipal heat governance to enable planning, accountability and evaluation. *(Correct—Amsterdam)* [10,20,24].
- Implement shared data governance for heat protection services, ensuring that municipal departments, public health bodies and community organisations use a common evidence register and update cycle. *(Address/Maintain—Amsterdam)* [10].
- Institutionalise vulnerability-weighted access targets (not only population-wide averages) and use them to prioritise investment in high-risk neighbourhoods. *(Exploit—Barcelona)* [27].
- Embed cooling standards into renewal and public-space projects (shade, ventilation, blue–green assets), treating them as baseline cooling infrastructure rather than optional greening. *(Maintain/Exploit—Copenhagen)* [21].
- Treat UHI mapping and monitoring as enabling infrastructure, with citywide datasets and repeatable evaluation protocols to target interventions and demonstrate effects over time. *(Correct/Exploit—Copenhagen)* [22].
- Standardise indicator provenance and comparability labelling ("municipality-reported" vs. "computed") and avoid benchmarking based on absolute counts or incompatible heatwave definitions. *(Address—cross-case)* [28].
- Integrate wayfinding and communication into activation protocols (public maps, signage, multilingual messaging, partner outreach) so refuges are not only available but used by high-risk groups. *(Maintain/Exploit—cross-case)* [10,20,24].

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